MODEL VALIDATION AND CHARACTERISTICS OF THE SERVICE LIFE OF JOHANNESBURG CONCRETE STRUCTURES

Dr. Stephen O. Ekolu
School of Civil and Environmental Engineering, University of the Witwatersrand
Private Bag, WITS 2050, Johannesburg, RSA.

ABSTRACT

Fifteen (15) reinforced concrete structures consisting of buildings in greater Johannesburg city area and major bridges at various motorway intersections were surveyed for active carbonation deterioration. This has been part of an ongoing field study conducted on the structures since 2000[1]. The data collected were used to validate a degradation model which was subsequently applied for probabilistic analysis of service life of the structures. The statistical variability for durability design parameters of compressive strength, carbonation depth, and carbonation rate were established. The field data verify the validity of an environmentally sensitive carbonation deterioration model. The probabilistic assessment results are compared with findings of the deterministic approach[1].

INTRODUCTION

In practically all global climatic conditions, corrosion of steel reinforcement is the most widespread durability problem in reinforced concrete structures. The predominant causes may vary depending of the exposure environment but will often be either carbonation or chloride attack. While the tropical climate prevails in Sub-Saharan Africa, coastal regions along the Indian Ocean and the Atlantic Ocean pose a severe environment of chloride laden exposure from seawater. South Africa (among other countries in the region) thus experience both carbonation and chloride attack. The processes associated with the attack is different for each of the mechanism, and in certain environments simultaneous attack from both mechanisms may result, causing more severe deterioration. Both mechanisms have been extensively studied in the literature[5, 6] over the past decades and scientific understanding of the deterioration processes have been developed. These principles are expressed as mathematical durability models for scientific applications.

However, application of these fundamental principles to estimate the rate of deterioration and effectively assess the end of service life of any given reinforced concrete structure is still a complex subject of research, yet to be fully understood. This is partly founded on the complexity and variability of ambient conditions, and response of the structure or material during interaction with its environment. Durability models can be applied to: (1) Planning and management of repairs or maintenance of structures. Inspection data collected is used in a durability model to forecast future time periods when repairs may be required for the various elements of the structure; (2) Risk analysis for structures whose failure bears major social, economic or ecological implications such as dams, bridges, nuclear power stations, oil platforms. Failure models are employed to assess critical path conditions aimed at minimizing the risk of failure.

Corrosion due to Carbonation

Steel in reinforced concrete is protected by high alkalinity (pH) sustained by a reservoir of calcium hydroxide from cement hydration. Carbonation results from CO_2 in air, typically 0.03% in rural areas and 0.3% in large cities, which penetrates into concrete through pore spaces and cracks. If moisture is present, CO_2 reacts with calcium hydroxide. The reaction results in lowering of the pH to critical levels, de-passivating steel and causing corrosion initiation. Carbonation attack commonly occurs in areas of high CO_2 concentrations and moderate relative humidity, 50 to 60% RH. Under saturated conditions, gas diffusion is hindered while under dry conditions, there is lack of moisture for chemical reaction to occur. Practically, the intermittent wet /dry cycles (representing moderate RH) is most conducive to carbonation corrosion. Also heating /cooling cycles from seasonal temperature variations may promote carbonation.

Deterministic versus Stochastic Models

Deterministic models do not consider variability of the design parameters. Typically, mean values of the parameters are used and only one value is generated as the output. These models are limited due to lack of ability to evaluate risk. More importantly, for phenomena where there are no definitive relationships, it is not possible to reliably apply deterministic models. Stochastic models are most appropriate in service life and durability design. Typically, stochastic models consider the variability of parameters. Structures are designed to achieve a minimum level of reliability as to function effectively over a target period of service life.

This paper is concerned with corrosion of steel reinforcement due to carbonation. This is the primary mechanism of interest for the data collected in the study conducted for reinforced structures in Johannesburg. Being an inland location, chloride attack is not a problem of concern as in most tropical inland areas of Sub-Saharan Africa. The service life analysis herein provided is a continuation of an ongoing research on durability, being conducted at Wits University since the field study presented in Lampacher[1], where durability assessment was done on fifteen (15) ageing concrete structures of 20 to 70 years consisting of major bridges and buildings in the greater Johannesburg region. The aims of this article are, to:

1. Establish the statistical characteristics of the service life variables for the Gauteng structures
2. Assess efficacy of a stochastic durability model for service life prediction
3. Evaluate and compare results from probabilistic and deterministic approaches

DURABILITY AND SERVICE LIFE

Service life is considered to be that period of use of a structure without any intervention or repairs, until the time when unacceptable deterioration level develops. This definition is based on Tutti's model[2], shown in Figure 1, associated with progressive development of damage within the structural material. It consists of two stages, of corrosion initiation during the time of ingress of deleterious agents through the concrete cover and the period of propagation where the electrochemical corrosion attack on the steel reinforcement occurs, increasing progressively with time to unacceptable level. The sub-stages of the damage propagation often relate to cracking, spalling, and delamination of concrete cover.

Whereas it is often the case that arrival of sufficient chloride levels to the level of steel almost always initiates corrosion attack, it is much more complex with carbonation as the environmental factors play a more significant role in this mechanism. It is therefore possible or even common for carbonation to occur past the level of the steel reinforcement in concrete with little or no sign of corrosion occurring. This complexity in carbonation mechanism is a difficult but necessary component that needs to be incorporated into the propagation period. It is often the case that, for chloride attack mechanism, service life (T_L) is deemed to end when critical levels of chloride contamination reach the steel reinforcement causing de-passivation. In generalized corrosion induced by carbonation, the end of service is normally extended to include the propagation time.

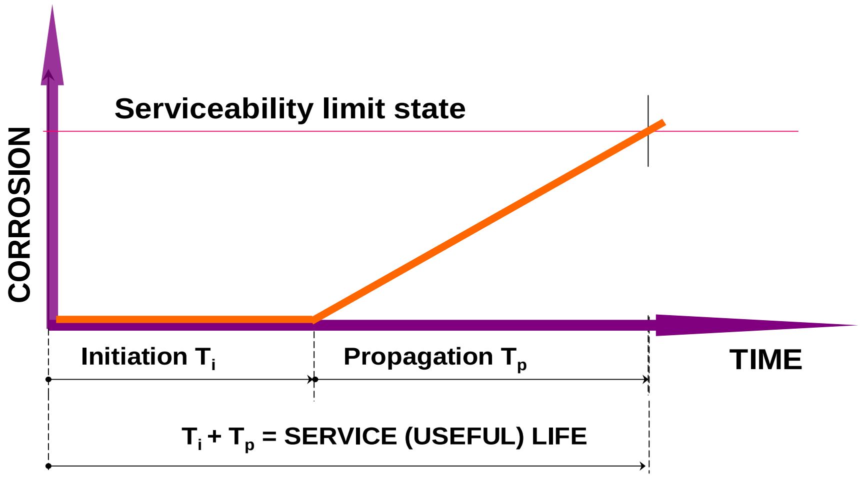

Figure 1: Theoretical service life model[2]

CARBONATION MODEL

The depth of carbonation is related to concrete characteristics by square root of time, given as.

$$\mu(X) = K_c\sqrt{t} \text{ and}$$
$$K_c = C_{env}C_{air}a(f_{ck}+8)^b$$

Where $\mu(X)$ = mean carbonation depth (mm)
K_c = coefficient of carbonation rate (mm/yr$^{0.5}$)
t = time of exposure (years)
C_{env} = environmental coefficient
C_{air} = air content coefficient
f_{ck} = characteristic cube compressive strength
a,b = constants dependant on binder type

Tables of coefficients and constants for use in the model can be found in the RILEM report[3].

The model allows for different environmental exposure conditions, strength and material characteristics of the concrete. The carbonation model only determines the time to steel depassivation but has no component of the corrosion propagation time to cracking.

STOCHASTIC METHOD OF DURABILITY DESIGN

Design problems are formulated according to the general principle that the resistance (R) of the structure to loading (S) must meet the criterion:

$$R - S \geq 0$$

The stochastic method considers the probability distributions of R, S and T_L as functions of time. The design condition is written as the probability of failure, being limited to a certain upper limit considered to be the unacceptable value. Normal distributions are suited for R and S while log-normal distributions apply to service life[3].

$$P(failure)_t = P(R - S < 0)_t < P_{fmax}$$

Where P_{fmax} = the max permissible failure probability

For normally distributed R and S, failure probability can be calculated using the reliability index β, expressed as:

$$\beta(t) = \frac{\mu[R,t] - \mu[S,t]}{\sqrt{\sigma^2[R,t] + \sigma^2[S,t]}}$$

Where μ = Indicates the mean of
σ = Standard deviation
β = the value along x-axis of NORMDIST curve (0,1)

Typically, 10% failure probability is adopted in standards or codes as the permissible upper serviceability limit[4]. The essential stages for estimating the service life by the stochastic method involves determination of the statistical variability of the influential parameters followed by calculation of the reliability index.

EVALUATION OF STATISTICAL VARIABILITY OF STOCHASTIC PARAMETERS

Reference is made to the investigation in Lampacher[1], whose data is herein treated to the carbonation model application. In the thesis[1], the depth of carbonation and compressive strengths were acquired along with classification of the structures as exposed or sheltered from rain. Also, important determinations consisted of the binder type used in the concrete. In this treatment of data, numerical values have been assigned to the various structures for purposes of analysis. Also included is the year of construction of the structure, as follows:

1 - Yale Telescope Bldg (1922), 2 - Harrow/Saratoga bridge (1962), 3 - Goch St South bridge (1965), 4 - Goch St North bridge, 5 - N4 bridge No 2597 Witbank (1966), 6 - Empire road bridge (1968), 7 - St Andrews Rd bridge (1968), 8 - Rissik st off/R M2E bridge (1968), 9 - M2 E/W bridge (Loveday str) 1968, 10 - Ponte Apartment Tower (1970), 11 - 1st Ave bridge (1971), 12 - Diepsloot 2nd bridge (1972), 13 - Diepsloot 3rd bridge (1972), 14 - Corlett drive bridge (1972), 15 - Booysens Rd on/off ramp bridge (1973).

The parameters governing service life can be seen directly from the model as: the environmental coefficient, air content coefficient, cover depth and compressive strength. For each structure, there parameters were determined except the depth of concrete cover which was assumed. The model considers the concrete cover thickness and depth of carbonation as stochastic quantities. Therefore, the coefficients of variation (CV) or standard deviations of these quantities are needed in the calculations.

Variability of Compressive Strength

Data consisting of three to six compressive strength values were obtained from each structure. The mean values and coefficients of variation were calculated. Results are reported in Figure 2 showing the CV for all structures. The average coefficient of variation for strength was found to be 0.17 (approximately CV = 0.2), which agrees with a CV value of 0.2 nominally used in the literature[3].

Variability of Carbonation Depth

For each structure, carbonation depths of up to ten measurements were determined from cores extracted from the structures. These values have been graphically analysed as shown in Figure 3. A coefficient of variation of 0.36 (approximately CV = 0.4) was obtained. In the literature, CV values in the range of 0.6 have been used[3].

Variability of Concrete Cover

In the investigation[1], no measurements of concrete cover thickness were determined. A specified cover of 25 mm was assumed for all structures. Consequently, there is no data present to statistically determine the coefficient of variation for concrete cover for the structures. For purposes of the model analysis, a CV value of 0.2 taken from the literature[3] was applied.

Variability of Carbonation Rate

From measurement of the carbonation depths and knowledge of the age of structures, the coefficient of carbonation rate were calculated for each structure. Figure 4 gives the coefficient of variation for the carbonation rate coefficient, which was determined to be 0.37 (approximately CV = 0.4), that is, the same as the CV of the carbonation depth measurements.

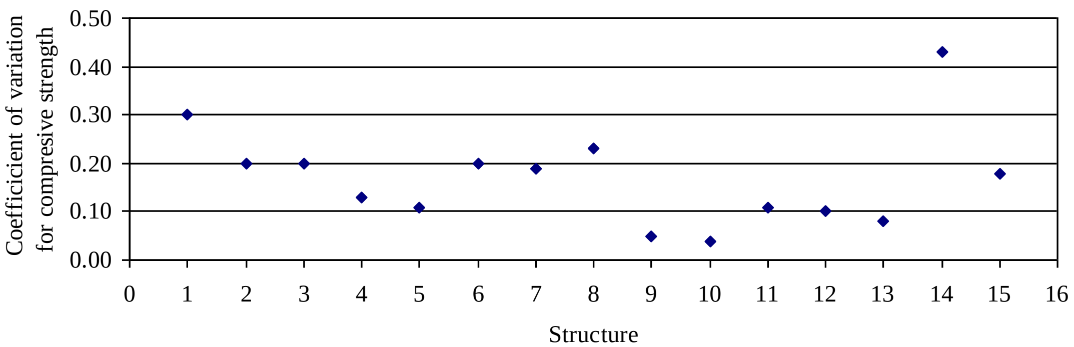

Figure 2: Coefficient of variation for compressive strengths of Johannesburg structures

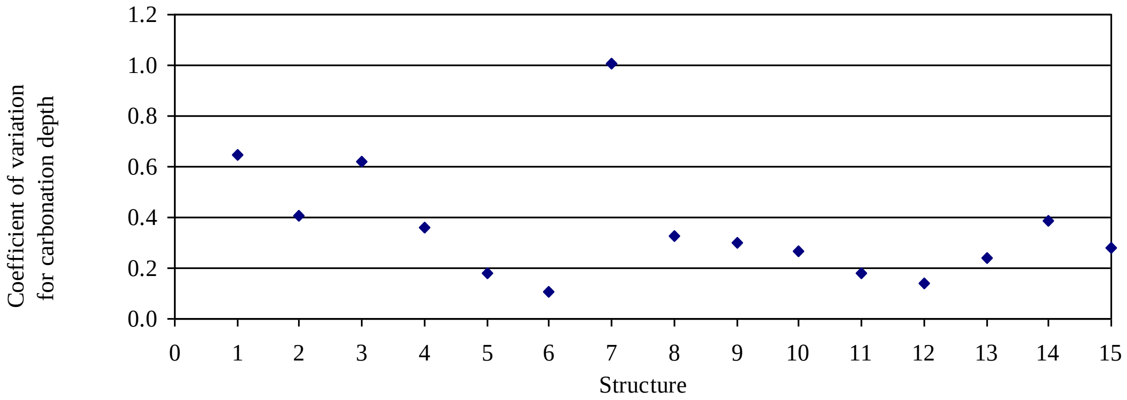

Figure 3: Coefficient of variation for carbonation depth measured for Johannesburg structures

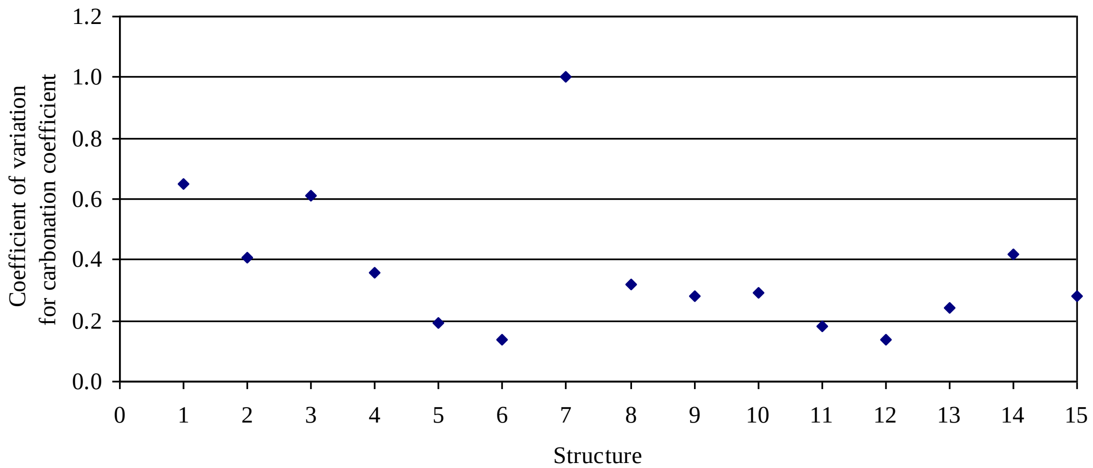

Figure 4: Coefficient of variation for carbonation rate of Johannesburg structures

MODEL VALIDATION

In assessing of service life, it was found necessary to first examine the accuracy and suitability of the carbonation model to reliably replicate the influence of exposure conditions in Johannesburg or Gauteng broadly. For this purpose, model calculations of carbonation rate coefficients were compared with actual coefficients determined from field carbonation results. The Model calculations were done basing on the following parameters and classifications:

1. All the structures are ‘sheltered’ from rain except Structure No. 1, which was considered ‘exposed’.
2. All the structures are CEM I concretes except Structures No. 5 and No. 10 whose binder type analysis was found to contain slag.
3. The mean compressive strengths measured for each structure are used. The strengths varied from structure to structure, ranging from about 30 to 60 N/mm^2.
4. The concrete cover thickness was assumed to be 25 mm, as per specifications. No actual field cover measurements were undertaken.

It is quite clear in Figure 5 that the carbonation model predictions strongly correlate with measured carbonation rate coefficients, along the line equality. The model can be considered to be accurate for assessment of deterioration of the structures.

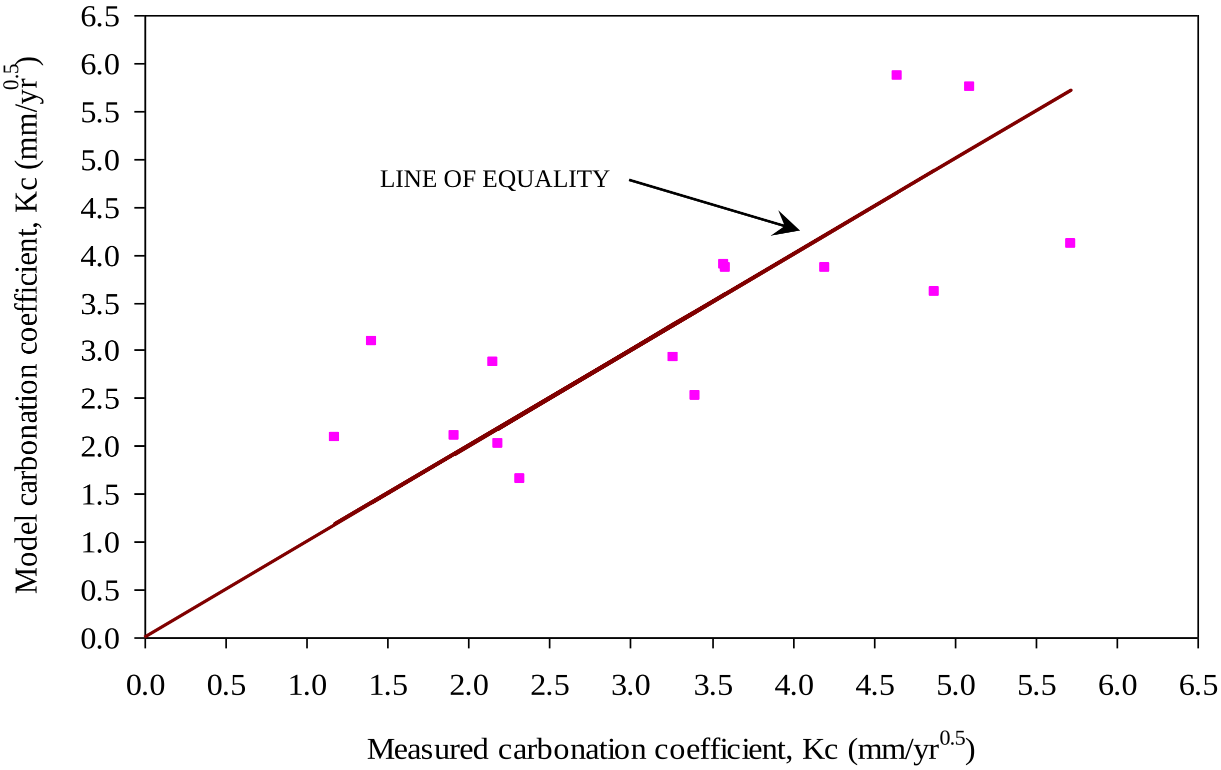

Figure 5: Model validation for carbonation of Johannesburg structures

PROBABILISTIC ASSESSEMENT OF SERVICE LIFE

The failure probability has been calculated as the distribution curve of carbonation depth that exceeds the concrete cover thickness. The corresponding failure probabilities are calculated for various time periods of service life. Calculations were done for each of the structures, producing the probability distribution functions given in Figures 6a,b,c. In Table 1, the time period to 10% failure probability is compared to the deterministic results obtained from test measurements. The results of carbonation measurements show depassivation to have occurred in three structures, *Harrow/Saratoga bridge, Rissik st off/R M2E bridge* and *M2 E/W bridge (Loveday Str).*

Interestingly, these results suggest that the oldest structure of 70 years (Yale Telescope building) has not reached depassivation, contrary to results of structures of similar strength values.

In comparison, the stochastic method found altogether five depassivated structures, to include *Yale Telescope building* and *N4 bridge No 2597 Witbank*, in addition to the previous structures listed from deterministic test measurements. A brief analysis indicates the probabilistic evaluation to be quite more plausible in its service life predictions.

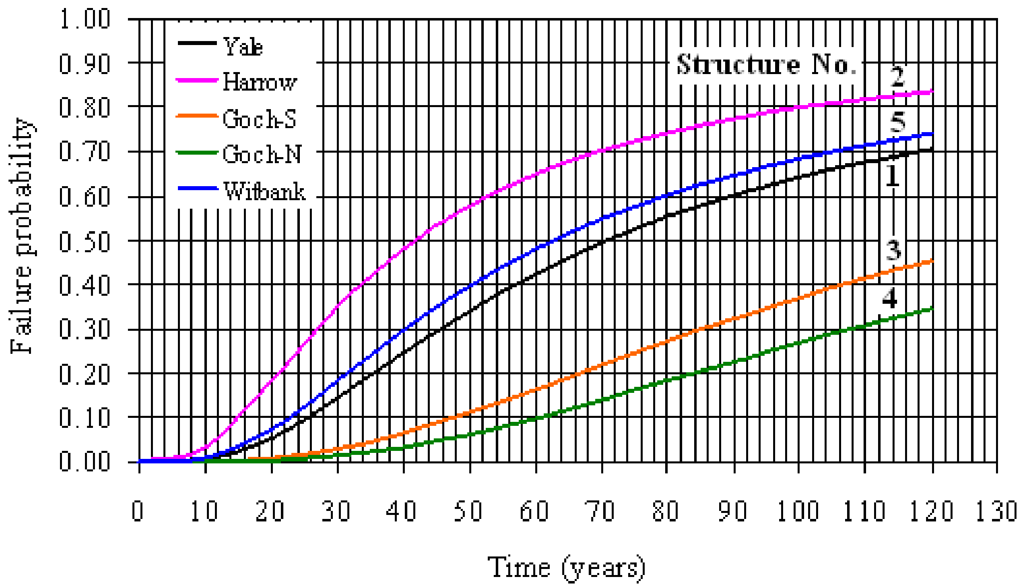

Figure 6a: Probability distribution function of service life for structures 1 to 5

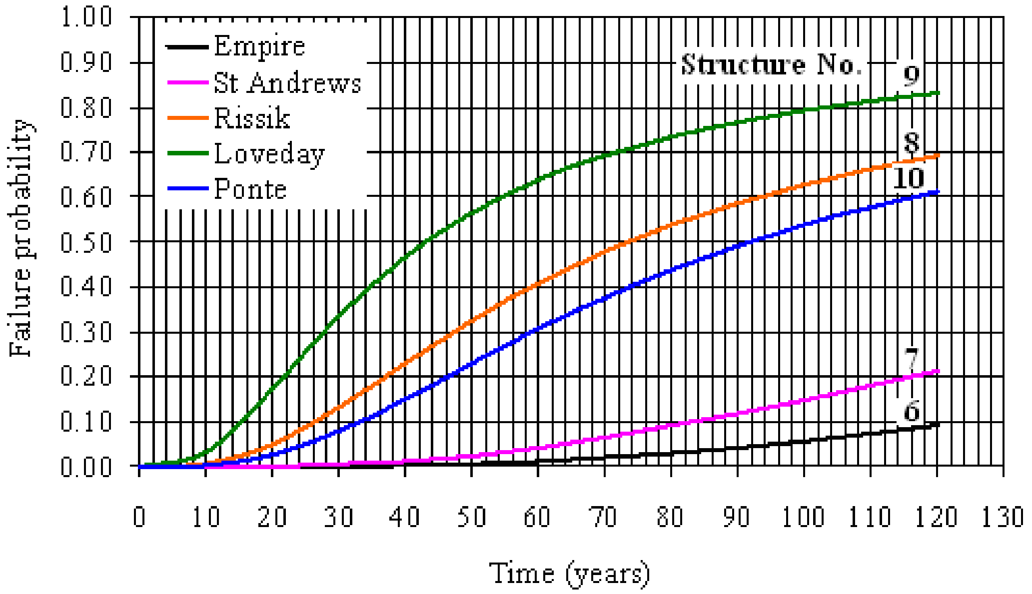

Figure 6b: Probability distribution function of service life for structures 6 to 10

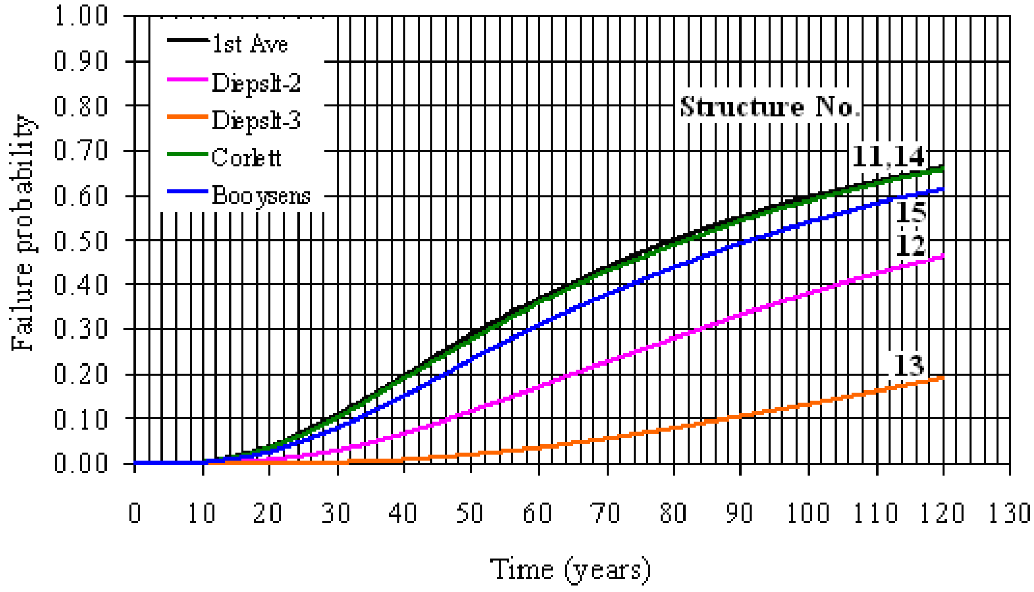

Figure 6c: Probability distribution function of service life for structures 11 to 15

Table 1: Service life evaluation of Johannesburg structures

Structure (No. and name)	Age (years)	Mean compressive strength (N/mm^2)	Mean Carbonation depth (mm)	Time to 10% failure probability (years)
1. Yale Telescope Bldg	70	35.3	15.9	25.6
2. Harrow/Saratoga bridge	30	29.1	25.5	14.7
3. Goch St South bridge	27	44.1	11.0	48.0
4. Goch St North bridge,	26	47.8	17.2	60.0
5. N4 bridge No 2597 Witbank	27	43.8	18.6	22.7
6. Empire road bridge	24	61.2	11.0	>120
7. St Andrews Rd bridge	24	53.4	6.0	83.3
8. Rissik st off/R M2E bridge	24	35.8	27.7	26.3
9. M2 E/W bridge (Loveday Str)	24	29.4	24.8	15.0
10. Ponte Apartment Tower	23	52.7	6.7	32.9
11. 1st Ave bridge	21	36.9	16.3	28.6
12. Diepsloot 2nd bridge	20	43.8	14.7	46.0
13. Diepsloot 3rd bridge	20	54.4	9.8	86.7
14. Corlett drive bridge	20	37.2	18.8	30.0
15. Booysens Rd ramp bridge	19	38.7	21.3	32.9

CONCLUSIONS

The stochastic method has been applied to service life estimation for Johannesburg structures. An environmentally sensitive carbonation deterioration model that allows for various environmental exposure conditions, strength and material characteristics of concrete was tested and found to reliably predict the carbonation rate under the Johannesburg conditions.

Statistical variability for stochastic quantities including the compressive strength and carbonation depth, were determined and found to be in good agreement with typical values used in the literature. Service life estimations from the stochastic method showed more plausible predictions when compared to ordinary deterministic measurements from tests. Further investigation is required to measure the depth of concrete cover of the structures and incorporate the corrosion component into the model in order to improve accuracy and potential efficacy of the service life prediction model.

REFERENCES

1. Lampacher, B. J., *Assessing the Durability of Concrete Structures*, Ph.D Thesis, School of Civil and Envir Engineering, University of the Witwatersrand, 2000, 212 p.
2. Tutti, K., *Corrosion of Steel in Concrete*, Report Fo 4 – 82, Cement and Concrete Research Institute, Stockholm, 1982.
3. RILEM, *Durability Design of Concrete Structures*, RILEM REPORT 14 (A. Sarja & E. Vesikari, Eds), E & FN Spon, UK, 1996, 165 p.
4. Gjorv, O.E., *Durability Design of Concrete Structures in Severe Environments*, Taylor and Francis, UK, 2009, 219 p.
5. Addis, B. and Owens, G. (eds.), *Fulton's Concrete Technology*, 8th Edition, 2001, Cement and Concrete Institute, Midrand, 330p.
6. CEB, *Durable Concrete Structures*, Design Guide, 1992, Thomas Thelford, 111p.